Vertically Integrated Liquid Water—A New Analysis Tool

DOUGLAS R. GREENE—*Techniques Development Laboratory, NOAA, Silver Spring, Md.*

ROBERT A. CLARK—*Department of Meteorology, Texas A&M University, College Station, Tex.*

ABSTRACT—Through the use of digital radar data measured at successive elevation angles in a storm system, we developed a technique that presents a new dimension in mesoscale analysis. This technique, mapped vertically integrated liquid-water content (VIL), presents the three-dimensional characteristics of a storm system in a two-dimensional display. This analysis technique appears to hold real promise for both severe storm and hydrologic applications.

1. INTRODUCTION

The space-time density of regular synoptic meteorological data is inadequate for many meteorological purposes. This data gap is partially filled by weather radars that can effectively scan a radius of 100 mi and, in some cases, an entire storm-producing area. In most cases, these radar data are reduced manually by field forecasters for short-range forecasting and issuing of storm warnings (Bigler et al. 1970). Manual techniques are frequently impractical because (1) the large quantities of data generated by the radar are too difficult to assimilate and (2) the visual extrapolation of radar data is often unreliable because of rapid changes in small-scale echo characteristics. The ultimate solution is "real-time" automatic computer processing and analysis of radar data. Steps were taken toward a real-time system with the development of the digitizing hardware and procedures for the WSR-57 by the National Severe Storms Laboratory (NSSL) of the National Oceanic and Atmospheric Administration (NOAA) and by the initiation in spring 1971 of an experiment in digitizing weather radar data from a four-station network by the National Weather Service (NWS), NOAA. Digital radar data have been used for hydrologic applications and by Barclay and Wilk (1970) to identify and track storms. However, the full potential of these data has not been fully exploited.

We are currently studying the feasibility of utilizing digital radar data for severe weather forecasting and hydrologic applications. The purpose of this paper is to preview some of our experiments and to report an analysis technique that presents a new dimension in the analysis of radar data.

2. DATA

Digital radar data used in this study were furnished by NSSL. The techniques used in the collection, processing, and recording of these data have been described in detail by Wilk et al. (1967). These data are presented in digital form for each 2° of azimuth at 1 n.mi. ranges for successive elevation angles in steps of one beam width (2°). By using the calibration data supplied in the digital record, one can convert these data to normalized power or radar reflectivity. It is frequently desirable to convert these data from the radar coordinate system to a system having the vertical direction as a coordinate. As part of our work, we have studied various coordinate systems, interpolation procedures, and grid intervals that will be reported on in a future paper. The analyses presented in this paper were performed by use of a quadratic interpolation procedure in a cylindrical coordinate system having a $2° \times 1$ n.mi. $\times 5,000$-ft grid interval. This coordinate system minimizes errors since interpolation is required only for the vertical coordinate.

3. CAZM PRESENTATIONS

If digital radar data are available for successive elevation angles in steps of one beam width, it is possible to construct constant altitude reflectivity maps (CAZM) for any desired level within the range of the data (figs. 1–3). On these maps, radar reflectivity, Z, values are expressed in dbZs; that is, the value plotted is $10 \log Z$, where Z is expressed in $m^6 \cdot m^{-3}$. These maps are similar to the constant altitude plan position indicator (CAPPI) presentations developed by Marshall at McGill University (Wein 1963). CAZM presentations in figures 1–3 clearly illustrate the storm intensity at three selected levels, thus allowing a three-dimensional interpretation of the echoes.[1] These presentations are very useful in meso-analysis and/or the study of thunderstorm dynamics. Although a CAZM illustrates the echo or storm intensity at various constant levels, to identify precisely the most intense echoes, one must look at the CAZM for each level and integrate mentally the intensities through the depth of the storm. An analysis technique and display that presents this three-dimensional characteristic in a two-dimensional display is presented in the next section.

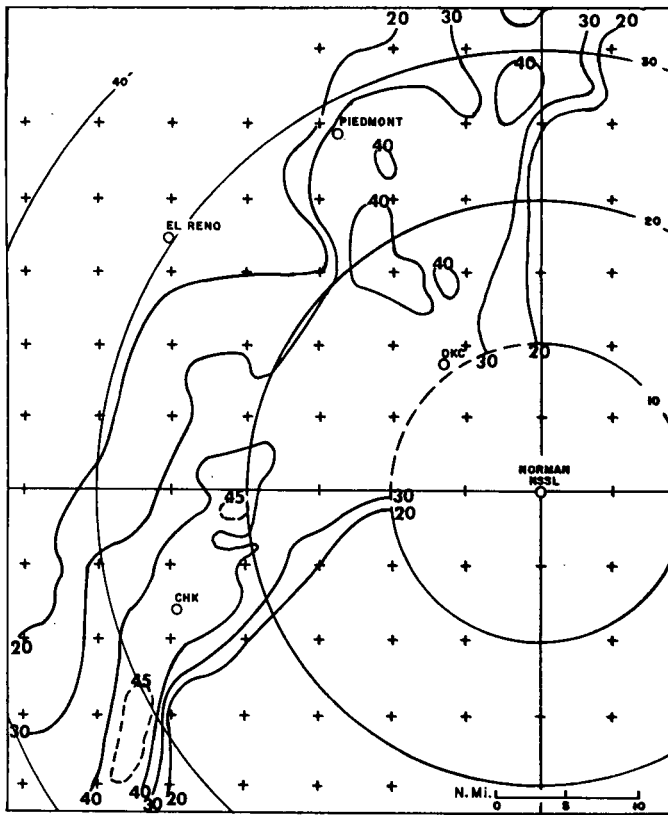[1] Technically, figure 1 is not a CAZM but is a map of 0° reflectivity.

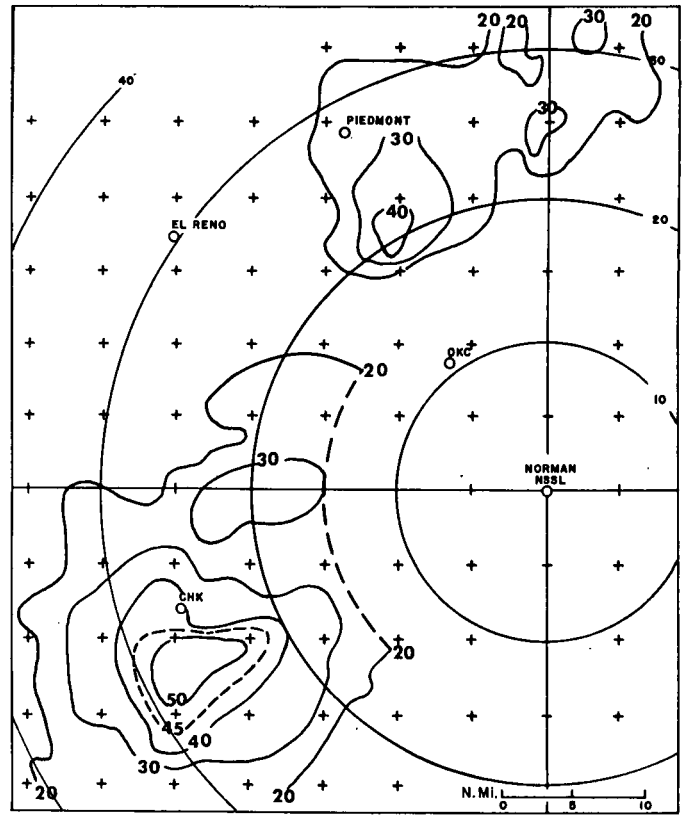FIGURE 1.—Zero-degree reflectivity in dbZs for 1650 CST, Apr. 26, 1969.

FIGURE 3.—CAZM at 30,000 ft for 1650–57 CST, Apr. 26, 1969

FIGURE 2.—CAZM at 10,000 ft for 1650–57 CST, Apr. 26, 1969.

4. VERTICALLY INTEGRATED LIQUID-WATER CONTENT (VIL)

The concentration of liquid water in a cloud is of considerable meteorological importance. Its magnitude and spatial distribution are important factors in the study of cloud dynamics since they indicate the degree of condensation and development that has taken place. Changes in the water content are important thermodynamically because they are accompanied by large energy changes (Mason 1957). Unfortunately, at this time there is no method of rapidly and accurately measuring the magnitude of liquid-water content; however, its relative magnitude and distribution may be determined by radar measurements if certain assumptions are made regarding the in-cloud drop-size distribution. An exponential drop-size distribution proposed by Marshall and Palmer (1948) seems to fit the distributions observed by several investigators. This distribution is given by

$$n(a) = N_0 \exp(-ba) \tag{1}$$

where a is the drop diameter, $n(a)$ is the number of drops of diameter a, and N_0 and b are parameters in the distribution.

To use radar as an indicator of liquid-water content, M, a relationship was obtained between M and radar reflectivity, Z. Mathematically, M and Z may be defined by

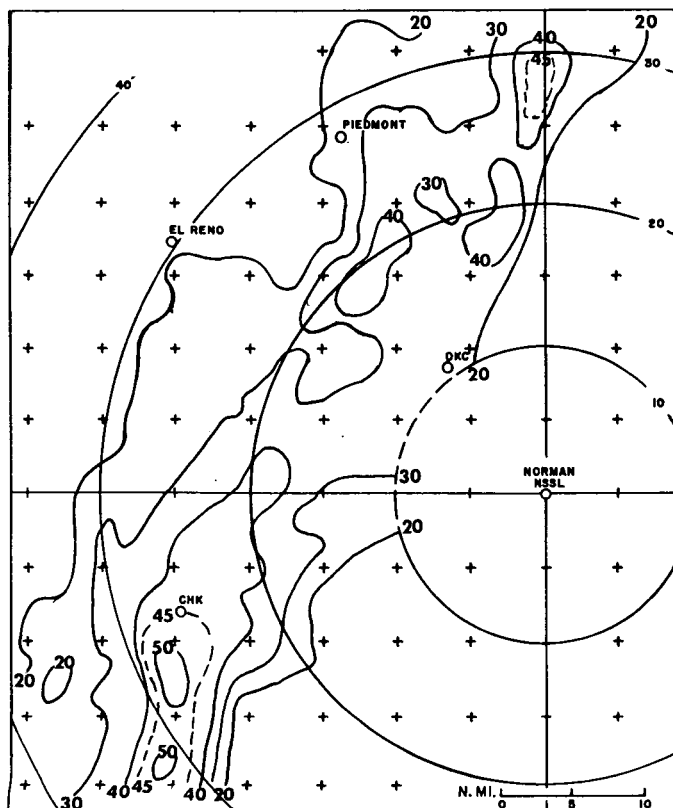$$M = \frac{\rho_w \pi}{6} \int_0^x n(a) a^3 \, da \tag{2}$$
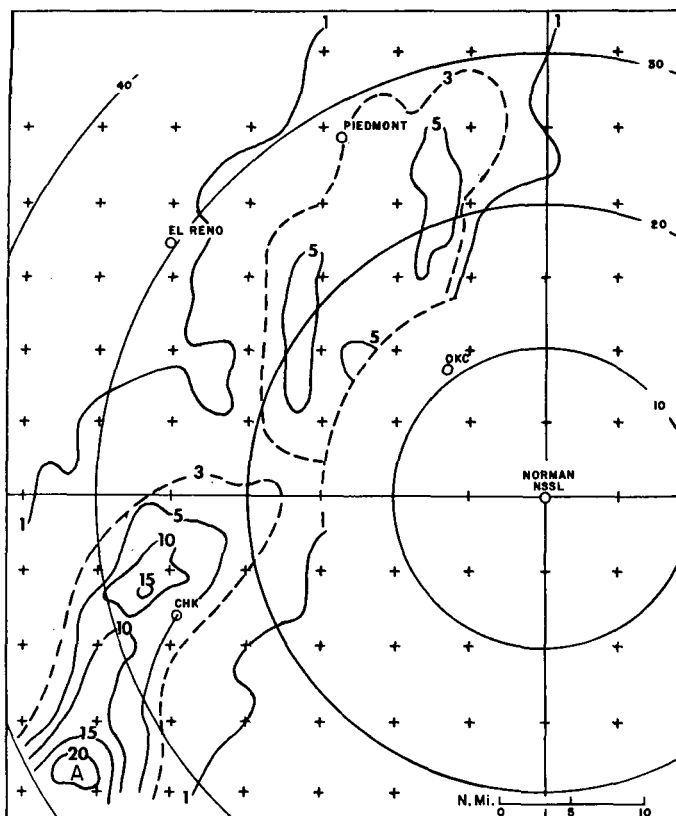
FIGURE 4.—VIL map for 1640-47 CST, Apr. 26, 1969. Isopleths of M^* are in kg·m^{-2}.

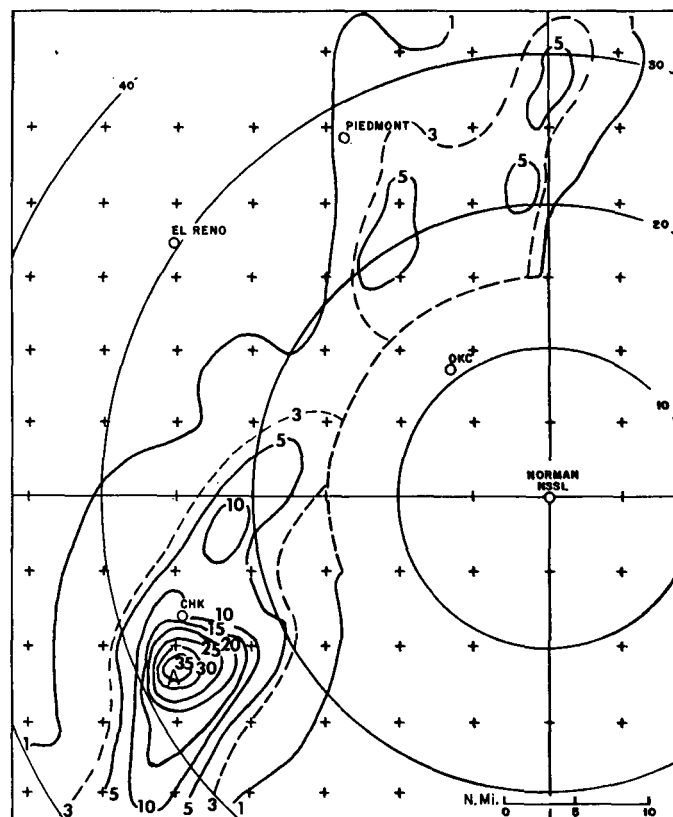FIGURE 5.—VIL map for 1650-57 CST, Apr. 26, 1969. Isopleths of M^* are in kg · m^{-2}.

and

$$Z=\int_0^x n(a)a^6 da \qquad (3)$$

where x is the maximum drop diameter and ρ_w is the density of water. When the Marshall-Palmer drop-size distribution is used in eq (2) and (3), the error is small if the upper limit of integration, x, is replaced by ∞. Integration yields

$$M=\frac{N_0\rho_w\pi}{6}\int_0^\infty \exp(-ba)\ a^3 da = \frac{N_0\rho_w\pi}{6}\ \frac{\Gamma(4)}{b^4}=\frac{N_0\rho_w\pi}{b^4} \qquad (4)$$

and

$$Z=N_0\int_0^\infty \exp(-ba)\ a^6\ da=\frac{N_0\Gamma(4)}{b^7}=\frac{720 N_0}{b^7}. \qquad (5)$$

Eliminating the parameter b between eq (4) and (5) yields

$$M=\frac{N_0\pi\rho_w}{[720 \times 10^{18} N_0]^{4/7}}\ Z^{4/7}. \qquad (6)$$

For $N_0 = 8 \times 10^6 $m^{-4} and $\rho_w = 10^6$ g/m^3,

$$M=3.44 \times 10^{-3}\ Z^{4/7} \qquad (7)$$

where the units of M are g·m^{-3} and of Z are mm^6·m^{-3}. The factor of 10^{18} in the denominator in eq (6) is required to convert the units of Z from m^6·m^{-3} as given in eq (5) to mm^6·m^{-3}.

M^* is defined as the vertically integrated liquid-water content of the storm and has units of mass per unit area. M^* is computed by integrating eq (7) from the base to the top of the echo; that is,

$$M^*=\int_{h_{base}}^{h_{top}} Mdh' =3.44\times 10^{-6}\int_{h_{base}}^{h_{top}} Z^{4/7}dh' \qquad (8)$$

where h' is the height expressed in meters and M^* has units of kg·m^{-2}. It should be noted that M and M^* represent the mass of raindrops in a unit volume and unit area, respectively. Since M^* is based on the relationship between M and Z, it would be incorrect to assume that M^* denotes all the in-cloud liquid water. Clouds containing a large number of small drops produce very small values of Z, which may be below the detectable signal of the WSR–57 radar, thus some liquid-water content, M, will not be detected. Hail may also produce fictitious values of liquid water due to enhanced radar return. However, this may be beneficial as an indicator of the severity of a storm.

VIL charts computed from digital radar data collected by NSSL during a storm event on Apr. 26, 1969, are presented in figures 4 and 5. The 5-min isohyetal maps corresponding to these times are presented in figures 6 and 7. The time of the isohyetal map in figure 7 corresponds to the 0° elevation Z map (fig. 1) and the VIL on figure 5. Since the VIL maps integrate over all levels, the configuration of echoes in figures 1–3 and that in figure 5 will be somewhat different. Values of M^* below 1 kg·m^{-2} were not depicted in figures 4 and 5. Visual comparison of these figures indicates that the VIL is possibly a better indicator of rainfall than 0° radar reflectivity. Detailed studies are currently being made to investigate the correlation of rainfall rate, R, with M^*.
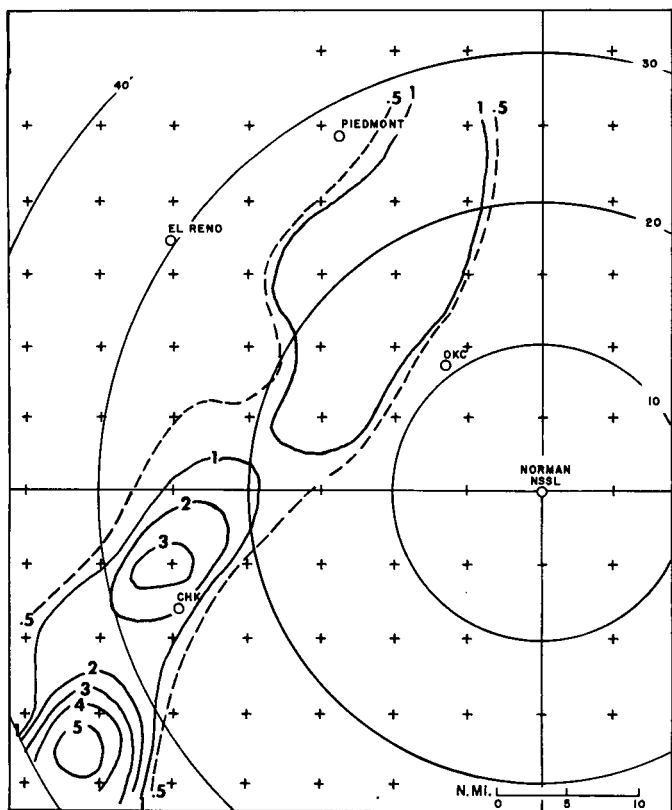
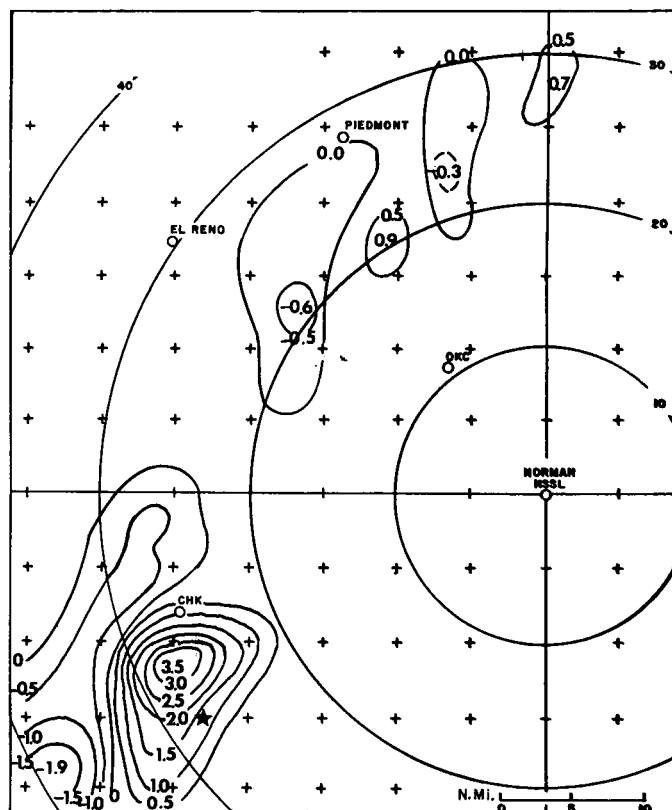FIGURE 6.—Five-min rainfall rate, R (in./hr), for 1640–45 CST, Apr. 26, 1969.

FIGURE 8.—Total change in M^* between 1640 and 1650 CST, Apr. 26, 1969. Isopleths are in kg · m^{-2} · min^{-1}. The star indicates the approximate location of a confirmed tornado.
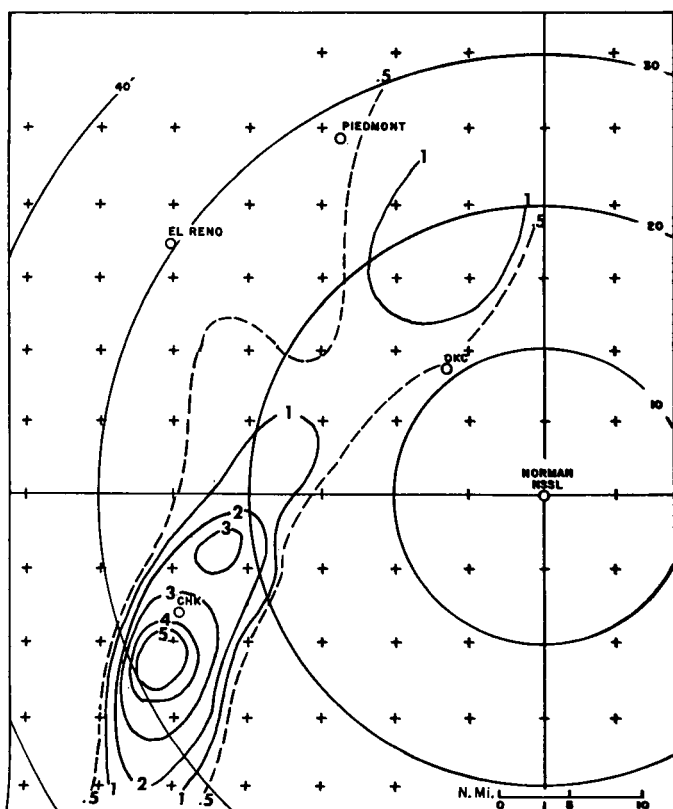

FIGURE 7.—Five-min rainfall rate, R (in./hr), for 1650–55 CST, Apr. 26, 1969.

VIL analyses also provide a new means for identification and possible forecasting of severe storms. The local change in M^* (i.e., $\partial M^*/\partial t$) for the time interval between the maps in figures 4 and 5 is shown in figure 8. It is of interest to note that, in a 10-min interval, the maximum M^* in echo A (figs. 4, 5) increased from 20 kg·m^{-2} to 35 kg·m^{-2}. This rapid increase in liquid-water content appears to be an indicator of "explosive development" of severe storms. At 1700 CST, just after this marked increase in M^*, a confirmed tornado occurred at the location of the star in figure 8. This suggests that the trend in M^* may be an indicator of severe weather development. Other cases with tornado occurrences are being studied to test this hypothesis.

There are many possible applications of the VIL analyses. For example, M^* may be computed from tilt digital data obtained from the national network of radar stations and a composite VIL formed. This composite would have many advantages over the present National Radar Summary Chart (NWS) because it would present an integrated three-dimensional display depicting the character and intensity of all storms in the network. The temporal nature of storm systems can be indicated by successive VIL's or by maps of $\partial M^*/\partial t$ similar to figure 8. This would approach the ultimate goal of the National Radar Network Display.

Although a large-scale digital computer was used to produce the VIL maps presented in this paper, with proper ordering of data, M^* values could be computed

on a "mini" computer at the radar site. Thus, M^* values would be readily available for real-time use.

Another advantage of vertically integrated values is that vertical integration will filter out strong radar returns that may be due to terrain features or nonstandard propagation. Although these returns may be very strong at low elevation angles, thus adversely affecting present Z–R relationships, they become insignificant when integrated over the vertical extent of the storm.

5. CONCLUSIONS

This preliminary investigation indicates that radar tilt data collected over short time intervals may prove to be very beneficial in both hydrologic and severe storm analyses. It is apparent that data collected at constant low antenna elevation angles may not reveal the complete character of a storm. A measure, such as total liquid water, yields an integrated morphology of severe storm systems.

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